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The Structural Performance of Traditional Oak Tension & Scarf Joints

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Summary

Renewed interest in the use of green oak and similar framing techniques, coupled with the restoration of historic framed buildings, has presented many structural engineers with difficulties when analysing the structural performance and integrity of traditional carpentry connections. At the University of Bath, there have been a number of research projects to investigate the engineering behaviour of traditional timber frames [1] [2]. This paper is a study of two types of traditional joint –scarf joints and tension joints. It gives limited data on the test results and postulates failure mode as a basis for further work.

1. Introduction

There is limited understanding of the engineering rationale behind the design of traditional carpentry joints. Instead joints have developed through the review of successful historic precedence by craftsmen. As a result the structural analysis of traditional joints is often over-conservative whilst certain joint configurations can become undesirable simply due to the uncertainty surrounding their design and structural performance [1] [2].

Since the 1980's, when there were approximately three to four timber framing companies practicing in the UK, the industry has grown significantly. There are now around a hundred timber framing companies in the UK creating a highly competitive niche market where the clientele expect high quality, durable frames. The historic foundation of the timber frame industry and the nature of the material mean that research has become an integral part in understanding the structural integrity and behaviour of structural oak carpentry.

This recent renaissance in the traditional timber industry has driven the need for structural engineers to further understand the mechanical behaviour of a technique which was historically designed and fabricated using the carpenters' rule of thumb, past precedence and a keen eye for geometrical proportions. As yet no specific design codes exist for traditional oak carpentry and previous quantitative analytical testing is relatively minimal.

In light of this situation a study has been carried out into the structural performance and behaviour of traditional oak scarf and tension joinery.

2. Sourcing & Fabrication of Joints

Although this study is concentrating on traditional carpentry joints, it was decided to source the joints from a company whose fabrication methods were rather more contemporary. Oakwrights Ltd. is one of only a handful of timber framing companies in the UK who use CAD-CAM techniques to create traditional and contemporary oak timber frames. With the aid of their Hundegger K2 cutting machine and its laser guided tools, it was possible to achieve tolerances of approximately 0.2mm.

This is beneficial as it removes almost any initial variation usually associated with hand crafted workmanship. Inevitably these high tolerances were still subject to the effects of shrinkage.

All timber lengths tested in this study were heartwood; some were boxed-heart and others halved beams. Initial concerns were raised about the grade and quality of the timber, some lengths contained relatively large knots and very steep grain angles which can affect the structural performance of the joint. Some sections had started to develop fissures along their lengths, due to tangential shrinkage. However, these fissures are completely natural within green oak timber frames and are not usually associated with significant loss of strength. Following a very simple grading guide, the timber was found to be grade THB.

In line with modern day traditional oak carpentry white oak turned tapered pegs were used for their uniformity, strength and stiffness. The pegs were fabricated from dry oak heartwood at approximately 10-12% moisture content. Section dimensions along with joint and peg configurations were determined through the guidance of experienced carpenters currently practicing within the industry.

3. Scarf Joint Introduction

Four types of Scarf joint were tested and analysed in an attempt to further understand the mechanics behind the transfer of bending forces through the joint. It is not uncommon that in modern restoration of frames the scarf joint will be required to carry bending moments. A scarf joint can be defined as, a joint for splicing timbers together end to end in order to create a longer member within the same profile. The jointing technique is widely recognised as being the strongest form of unglued member lengthening [3]. The earliest examples of splayed Scarf joints to be found in the UK were discovered on the Sutton Hoo ship [4] proving the immediate source of splayed scarfs in England to be of European origin. No doubt plainer, simpler joints were used beforehand though there is minimal documentation.

There are three main classes of Scarf joint [5]; halved, splayed and bridled. A halved scarf is a lap whose surfaces are parallel with the timbers', it is structurally the simplest, and the easiest to manufacture. This has led to this joint becoming the most widely used. A splayed scarf has the lapped surfaces sloping (a bridled scarf adds tenons). A bridled scarf takes the form of an open mortice and tenon.

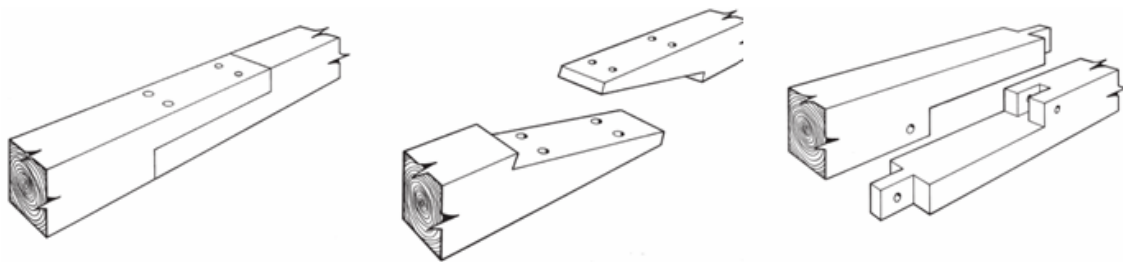


Fig. 1 – Halved, splayed and bridled scarf joints

Two timbers connected using traditional scarf jointing techniques cannot match the strength and stiffness of a single member of the same dimensions. A study carried out by TRADA into table scarf joints under bending loads suggested that their limiting moment capacity was equal to only a third of the strength of an equivalent un-jointed beam [6]. Due to their low bending capacity it has been historically understood that a scarf joint within a frame should be located where the bending moments are low in order to minimise the deflection. This initiative has carried through to modern design of traditional frames where the joint can be found either over a post or a brace.

4. Scarf joint testing

4.1 Design

The beam sections tested were 200 X 150 mm (8" X 6"), the most commonly used section dimensions for top plates within an oak timber frame. All peg holes were 19mm (3/4") in diameter and in keeping with traditional practice the peg holes on one side of the scarf were offset by 3mm with respect to the other side of the joint, tightening the joint when the pegs were driven through.

Four different types of scarf joint were selected; the under-squinted butt in halved scarf with two pegs, side-halved & bridled with two pegs, stop-splayed & tabled scarf with key and four pegs, and the face-halved and bridled scarf with four pegs. These joints were chosen based upon carpenters guidance and a need for good structural comparison. Diagrams of the four joints are respectively organised in Fig. 2 below.

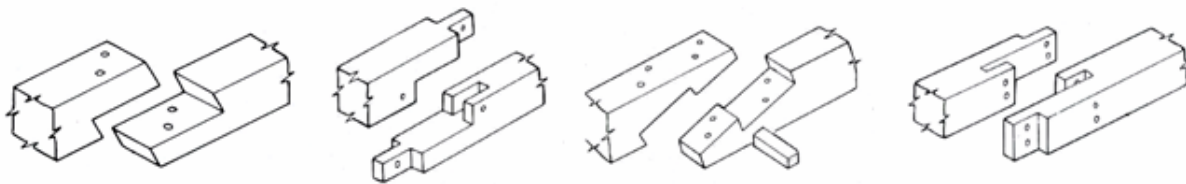


Fig. 2 – Scarf joint selection

4.2 Testing Procedure

The four joint types were tested in both pure vertical bending and pure lateral bending, individualising the actions imposed on the joint within a timber frame. Two solid sections were also tested for comparison and to generate a performance factor for the scarfed joints with respect to the total moment capacity of the solid sections.

To find the moment resistance of the joint, a four-point bending setup was adopted so pure, constant bending could be applied across the joint with no imparted shear. Both supports were pinned, one horizontally restrained and the other on a roller support. A number of transducers were placed on the top face of the beams at desired positions to measure vertical, downward displacements and one at the beam end, the end supported by the roller support, to measure horizontal displacement. The readings were collected via automated data acquisition software. All spans within the bendings test were kept constant with the load application at the quarter span points.

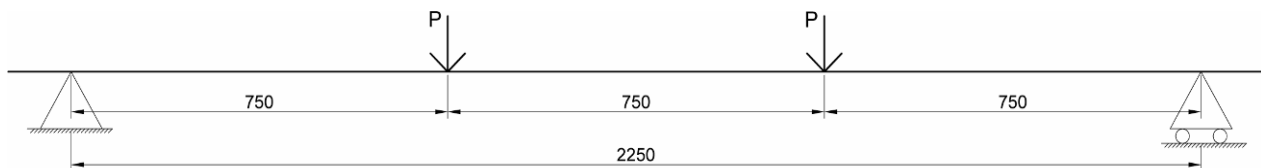


Fig. 3 – Test layout

The scarfed joints were all 2.5m long and the solid sections were all 1.5m long. Calculations were carried out to convert the strength and stiffness of the 1.5m solid beams into equivalent 2.5m long solid sections for direct comparison to the jointed beams.

5. Results, Analysis & Discussion

All beams showed an initial near-linear response to small load though in general timber can be said to be a non-linear inelastic material

The laterally loaded configuration of the side-halved & bridled joint was the stiffest joint out of all eight bending tests. This is a result of the greater lever-arm between the pegs and the greater depth

of the section used to transfer the bending stresses. This joint also displayed the greatest strength although at unserviceable deflections. The improved performance of this joint can in part be attributed to its use of pegs.

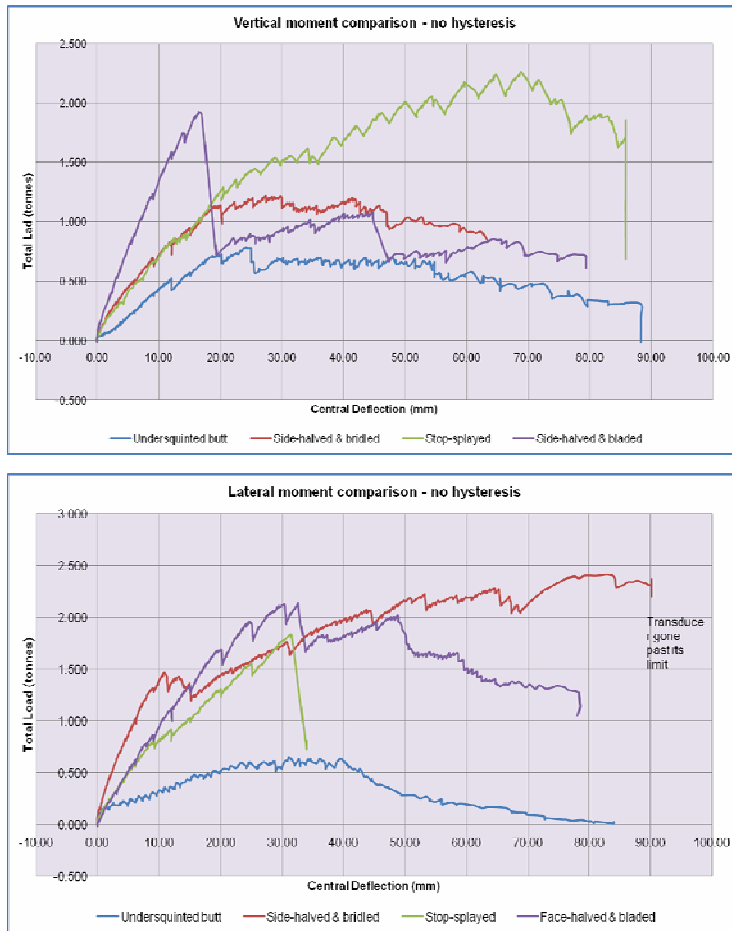


Fig.4 – Load v. Displacement outputs

Joint	Jointed Stiffness (kNm/mm)	Solid section stiffness (kNm/mm)	Performance factor
Vertical bending			
Undersquinted butt	0.44	1.20	0.37
Side-halved & bridled	0.79	1.20	0.66
Stop-splayed	0.75	1.20	0.63
Face-halved & bladed	1.32	1.20	1.10
Lateral bending			
Undersquinted butt	N/A	1.80	N/A
Side-halved & bridled	1.61	1.80	0.89
Stop-splayed	0.92	1.80	0.51
Face-halved & bladed	0.96	1.80	0.53

Joint	Jointed Mmax (kNm)	Solid section Mmax (kNm)	Performance factor
Vertical bending			
Undersquinted butt	2.94	29.90	0.10
Side-halved & bridled	4.53	29.90	0.15
Stop-splayed	8.47	29.90	0.28
Face-halved & bladed	7.22	29.90	0.24
Lateral bending			
Undersquinted butt	2.43	45.80	0.05
Side-halved & bridled	8.90	45.80	0.19
Stop-splayed	6.86	45.80	0.15
Face-halved & bladed	7.96	45.80	0.17

Table 1 Strength and stiffness performance factors

The pegs were critical elements in all eight tests. The failure of each joint was through cleavage of the main timbers and not through shear of the pegs. Cleavage of the timber required less energy than shearing the pegs, highlighting the importance of ensuring the pegs are of high quality and that in the case of historic frames they are structurally sound. By demonstrating that failure can be limited to cleavage, the capacity of the joint can be more readily predicted. Equivalent values of stiffness obtained from solid section testing were deemed unreliable in some cases due to the variations in the timber used. It is felt that this reduced the value of Young's Modulus for the solid section specimens. This is evident from reviewing the stiffness performance factors, which are extremely high. In one particular case the jointed section is stiffer than an unjointed section (*Fig. 4*)

The bending performance factors compare well to published results. Although some of the laterally loaded specimens were able to use the full depth of the 200mm deep beam, there was no significant increase in the maximum moment when compared to their vertically loaded counterparts. This can be attributed to the critical failure mechanism within most of the joints which was cleavage, (*Fig. 5*). This attributed to the ultimate failure within all of the joints as opposed to shear.

In conclusion it can be reported that all joints displayed considerable ductility under load and close to failure.

It is apparent from the results obtained that whilst designing a scarf joint the important factors to consider are:

1. Length of overlap – a longer overlap provides improved performance
2. To optimise the use of pegs.
3. Orientation of joint to load – most of the joints which were orientated to concentrate the forces on the pegs displayed a stiffer response.



Fig. 5 Cleavage initiation on side-halved joint

6. Traditional Oak Tension joints

Widespread use of the mortice and tenon joint has meant that traditional joints specifically designed to resist tension have become somewhat overshadowed, both in terms of present day construction and in the field of research. As such the structural performance and behaviour of traditional oak tension joinery is poorly understood. This study investigated the structural performance of three traditional timber joints used to carry tension forces in frame construction. These joints were the lap dovetail, lap cog, and the through-wedged half dovetail. The through-wedged dovetail is not discussed any further in this paper.

In light of the ambiguity surrounding the performance of traditional tension joinery, testing of the three joints outlined above was undertaken in order to investigate the failure behaviour and peak load characteristics. The dominant focus of this study was on the lap dovetail joint, in particular the influence of roof loading was tested for both the cog and dovetail lap joint. The shear resistance provided by the surrounding timber was also investigated.

7. Design and testing of tension joints

The dimensions of the joints are set out below and are representative of those used in practice. The main timbers were 155 mm wide X 195 mm deep, the dovetail tapered in 38 mm over the 155 mm member width and was 38 mm deep; the cog bearing section was 25 mm high and 38 mm wide.

All joints were loaded in pure tension under short term loading. The tests were terminated at connection failure which was defined as a complete loss of load resistance. This generally corresponded to the complete withdrawal of the vertical member. Throughout the loading of the specimens the displacements of the cross beam and the relative vertical displacements of the tension members were recorded in conjunction with the applied load.

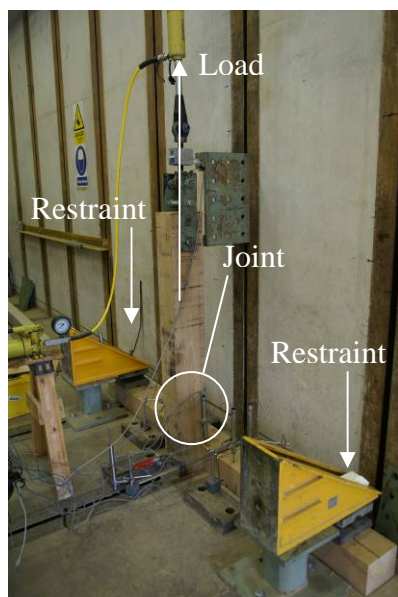


Fig. 6 Testing setup

The experimental setup was common for all the joints tested and is shown in Fig. 6. Due to space restrictions it was necessary to test the specimens in the vertical alignment shown. The load was applied using a hydraulic jack which had full articulation between itself and the loaded member in order to minimise the effects of any load eccentricity. Failure of the specimens was reached in six to ten minutes.

8. Simulated roof loading tests

Typically a lap dovetail and a lap cog joint would be used to resist the thrust of a main rafter. The load from the rafter provides a resultant normal force onto the lap joint, which was anticipated to increase the stiffness of the joints due to the increased frictional forces present. It was therefore decided that testing should attempt to quantify any improvement in performance associated with an additional normal force. Initially four lap dovetail joints and one lap cog joint were tested without the additional normal force, to provide benchmark performance characteristics from which comparisons could be drawn.

The normal force was applied centrally to the overlapping area of the joints through the use of a hydraulic hand pump. A bridge bearing was used as the interface between the jack and the timber in order to allow movement of the joint with minimal external frictional effects, whilst retaining a constant distributed load. An initial normal force of 600 kg was applied to the lap cog joint. This was based upon the load likely to be experienced in service under a roof truss spanning 5 m at 3 m centres. Two lap dovetail joints were tested with an additional normal force of 250 kg and 500 kg respectively, with the aim of quantifying the effects further.

9. Results of simulated roof loading tests



Fig. 7 Failure of lap dovetail joint



Fig. 8 Failure of lap cog joint

All the lap dovetail joints, including those with an additional normal force, failed due to the cross member splitting as the vertical member was pulled out. The vertical members suffered very little damage during the failure of the joint. Predominantly the cross members tended to split flush to the back of the dovetail rebate and the timber would then shear at a depth approximately equal to the thickness of the dovetail (Fig. 7). In general only one of the two sides bearing on the dovetail completely failed by splitting. The opposite side displayed some cracking but to a much lesser extent. The failure pattern was related to the grain pattern and was influenced by weaknesses in the members such as knots. One exception to this series of failures was the complete failure of the cross member. The splitting began in the same fashion as the other tests, flush with the back of the dovetail rebate. However due to an unforeseen flaw the split ran through the full depth of the cross beam resulting in complete failure. The joint, which is listed as test two in the results table, showed no significant loss of strength in comparison with the other joints.

The lap cog failed in a similar way to the lap dovetails, in that the cross member failed due to splitting along the grain whilst the vertical member remained relatively undamaged. Shown in Fig. 8, the cross member split failure can be seen to clearly

follow the grain in line with the raised section upon which the cog bears. The failure mode of the joint with the additional normal force was almost identical to that of the non-loaded connection.

The results for both the lap dovetail and the lap cog joints are presented in tables 2 and 3 below. It can be seen that for the lap dovetail joint no added performance is gained with the addition of the normal force. The peak load of both the lap dovetail joints tested with an additional normal force fell within the normal range of the other four joints tested. Although the initial stiffness of these two joints showed some improvement, the overall stiffness of the joint was very similar to that of the non loaded connections. The failure patterns and load displacement responses also followed the same trend as the standard tests.

For the lap cog joint the addition of the normal force appeared to improve the performance of the joint both in terms of stiffness and peak load. However, as only one of each of the joint setups was tested this observation is unreliable.

Table 2 Lap dovetail joints results

Test	Added normal force	Stiffness* (kN/mm)	Peak load (kN)
1	No	2.4	38.5
2	No	3.1	31.0
3	No	6.6	39.4
4	No	2.1	23.7
5	Yes (2.5 kN)	6.0	35.3
6	Yes (4.9 kN)	8.5	23.0

* Between 0 and 1 mm displacement

Table 3 Lap cog joint results

Test	Added normal force	Stiffness* (kN/mm)	Peak load (kN)
1	No	6.3	17.4
2	Yes (5.9 kN)	10.2	23.8

* Between 0 and 1 mm displacement

The testing of the lap dovetail and the lap cog have allowed the following conclusions to be drawn:

1. The lap cog generally provides a stiffer connection, primarily due to the 'fit' of the connection.
2. The lap dovetail joints fail in a more ductile manor than the lap cog. This is due in part to the initial absorption of energy in crushing the dovetail side walls and later on from the greater area of timber able to split during withdrawal of the dovetail. The lap cog joints were seen to fail with a single split parallel with the cog tooth which resulted in a rapid loss of strength.
3. The addition of a simulated roof load onto the lap dovetail was not shown to significantly enhance performance. The lap cog joint did show improved performance with the additional normal load. However the number of specimens tested means that this cannot be categorically concluded.

10. Lap dovetail shear restraint tests

The failure mode of the dovetail lap joint was seen to be similar to that shown in Fig. 7 for each of the first six tests. Based upon this observation it was decided that a series of tests would be carried out to investigate the behaviour of the area of timber providing restraint against withdrawal of the dovetail. The area of failure was controlled by cutting slots beside the dovetail of equal depth, thus limiting the shear area. It was anticipated that this would provide an insight into the distribution of stresses over the shear area and potentially provide the basis for a simple conservative design check

based upon the shear strength of oak and size of dovetail.

A total of seven joints were tested with slot configurations running vertically and diagonally in order to control the splitting length of timber. The diagonal slots were intended to estimate the shear failure seen in previous testing and the vertical slots were intended to force the failure closer to the dovetail and reduce the risk of splits running beyond the limited area.

The testing demonstrated that a conservative calculation of the joints strength could be carried out using the shear strength of the oak perpendicular to the grain and an informed estimate of the shear area. Further work is required in this area to quantify the parameters which define the failure area.

The following conclusions were drawn from the shear restraint tests.

1. The method of testing was on the whole successful in constraining the failure of the cross member to a specific area.
2. The diagonally constrained areas failed by rapidly shearing across the entire area at critical load. This suggests that shear stress is carried evenly across the section and provides the opportunity to develop a critical geometry that defines the point at which failure becomes uneven.
3. A critical geometry such as this would allow a conservative design strength to be calculated based upon the timber shear strength perpendicular to the grain and the critical area.

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